SOLVING TWO PUZZLES IN ONE GO: QUINTESSENCE FROM A DECAYING DARK MATTER

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The mystery of the Dark energy is not just its smallness. The extreme fine tuning of its density in the Early Universe such that it permits galaxy formation before creating a new inflationary epoch is its other unexplained aspect. Here we propose a model based on the very slow decay of a Super Heavy Dark Matter (SDM), presumed candidate for the origin of the Ultra High Energy Cosmic Rays (UHECRs). A small part of the remnants energy is in the form of a scalar field which decoheres and behaves like a quintessence field. This model does not need a special form for the potential and a simple ϕ^4 theory or an axion like scalar is enough. The equation of state of the Dark Energy becomes very close to a cosmological constant and is very well consistent with observations.

In *Classical* Quintessence models a number of important issues are left unexplained. The complex behaviour of the potential they need is difficult to obtain from the Standard Model of particle physics or its extensions. In its simplest form it can not provide the observed $w_q \lesssim -1$ and does not explain the extreme relation between the Dark Matter (DM) and the Dark Energy (DE) density in the Early Universe.

Most solutions which have been recently proposed for resolving the latter problem are focused on the interaction of the quintessence scalar field ϕ_q with the dark matter [1 2 3 4]. These models however don't have $w_q \lesssim -1$ (although the main idea can be applied to the more complex quintessence models with unconventional kinetic term or non-minimal coupling to gravity). Some lead to a variable mass for DM particles which is very strongly constrained by the CMB anisotropy observations [5].

What we propose here [6] is a model for dark energy somehow different from previous quintessence models. We assume that DE is the result of the condensation of a scalar field produced during very slow decay of a massive particle. The main motivation is the possibility of a top-down solution [7 8] for the mystery of UHECRs [9 10]. If a very small part of the decay remnants which make the primaries of UHECRs is composed of a scalar field ϕ_q, its condensation can have all the characteristics of a quintessence field. Moreover, it has been demonstrated that the cosmological equation of state for a decaying dark matter in presence of a cosmological constant

is similar to a quintessence with $w_q \lesssim -1$ [11]. The latest estimation of w_q from high quality SN-Ia light curves is $w_q = -1.05^{+0.15}_{-0.20}$ [12]. The mean value is exactly in the range predicted for a decaying dark matter with a lifetime $\tau \sim 5\tau_0$ where τ_0 is the present age of the Universe [11] (The error bars however are too large to make a definitive conclusion possible). This lifetime for a $M_{dm} \sim 10^{24} eV$ can also explain the observed flux of UHECRs without violating the present limits on the high energy neutrinos or photons [8]. Therefore it seems that both observations point to a top-down solution which explains simultaneously the dark energy and the UHECRs.

The effective Lagrangian can be written as:

$$\mathcal{L} = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi_x\partial_\nu\phi_x + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi_q\partial_\nu\phi_q - V(\phi_x, \phi_q, J)\right] + \mathcal{L}_J \qquad (1)$$

where scalar fields ϕ_x and ϕ_q are respectively SDM and the quintessence. The field J presents collectively other fields. The term $V(\phi_x, \phi_q, J)$ includes all interactions including self-interaction potential for ϕ_x and ϕ_q:

$$V(\phi_x, \phi_q, J) = V_q(\phi_q) + V_x(\phi_x) + g{\phi_x}^2{\phi_q}^2 + W(\phi_x, \phi_q, J) \qquad (2)$$

The term $g{\phi_x}^2{\phi_q}^2$ is important because it is responsible for the annihilation of X and back reaction of the quintessence field. $W(\phi_x, \phi_q, J)$ presents interactions which contribute to the decay of X to light fields and to ϕ_q (in addition to what is shown explicitly in (2)). After writing the dynamical equations for the fields, one obtains the following asymptotic solution for ϕ_q when its time variation is slowed down:

$$V_q(\phi_q) = V_q(\phi_q(t'_0)) + \Gamma_q\rho_x(t'_0)\int_{t'_0}^{t} dt\left(\frac{a(t'_0)}{a(t)}\right)^3 e^{-\Gamma(t-t'_0)} \qquad (3)$$

where Γ and Γ_q are respectively the total decay width and the width for the decay of the SDM to ϕ_q. ρ_x is the density of the dark matter and t'_0 is the initial time for this asymptotic regime. If the slow down happens long before the matter-radiation equilibrium, at $\sim 100t'_0$ the energy density of ϕ_q is $\sim 90\%$ of its final value. This

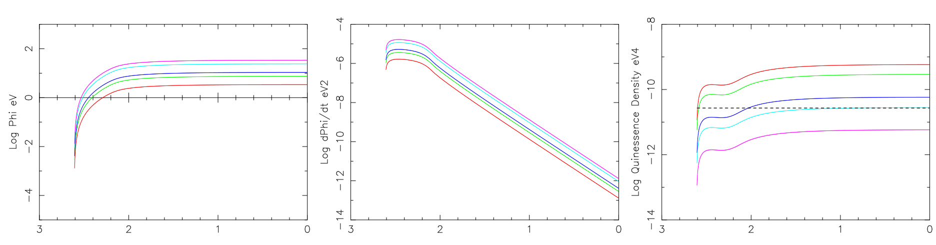

Figure 1. Evolution of quintessence field (left), its derivative (center) and its total energy density (right) for bottom to top curves $\Gamma_0 \equiv \Gamma_q/\Gamma = 10^{-16}$, $5\Gamma_0$, $10\Gamma_0$, $50\Gamma_0$, $100\Gamma_0$. Dash line is the observed value of the dark energy. $m_q = 10^{-6}eV$, $\lambda = 10^{-20}$.

result has been also confirmed by the numerical solution of the evolution equations.

Fig.1 and additional figures in [6] show that in a few orders of magnitude in redshift after the production of SDM, ϕ_q approaches a saturation and its energy density changes very slowly. The details of the model depend on the self-coupling and mass, but general behaviour of the ϕ_q field is quite stable. Parameters can be changed by many orders of magnitude without destroying the general behavior of the equation of state or the extreme relation between the energy density of dark energy and the total energy density in the early Universe. Therefore like other models with interaction between DM and DE, in this model the coincidence problem is solved without fine-tuning. Evidently this model does not explain the hierarchy of couplings and masses. But the relative value of these quantities are less extreme than the Cosmological Constant and the Plank mass. It has also been shown that the spatial perturbation of ϕ_q is very small and decays with time. The effect on the CMB angular spectrum and Large Structures is very small and consistent with observations. All these properties are the consequence of the large lifetime of the SDM. In most quintessence models the scalar field is produced during inflation or reheating period in large amount and needs a negative exponential or a negative power function to control its contribution to the total energy of the Universe.

The issue of decoherence of ϕ_q in this model is not trivial and needs more investigation. The minimum condition for mode k to decohere is [13]: $k^2/a^2+{m_q}^2 \lesssim H^2$ where H^2 is the Hubble Constant. If the SDM exists and is produced during preheating just after the end of the inflation presumably at $T \sim 10^{14}eV - 10^{16}eV$ scalars with mass $m \lesssim 10^{-6}eV$ can decohere. When the size of the Universe get larger, ϕ_q stops decohering. This also helps having a very small dark energy density.

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